Apparent softening of the symmetry energy with the inclusion of non-nucleonic components in nuclear matter

JIANG Weizhou*

Department of Physics, Southeast University, Nanjing 211189, China

Abstract Apparent softening of the symmetry energy with the inclusion of hyperon and quark degrees of freedom is demonstrated by the fact that the phase transition causes the change of the interaction and the suppression of nucleon fractions. The demonstration is fulfilled in the relativistic mean-field model.

Key words Symmetry energy, Nuclear matter, Relativistic mean-field model

1 Introduction

The nuclear symmetry energy of isospin asymmetric nuclear matter is important to understand the structure of neutron- or proton-rich nuclei, the reaction dynamics of heavy-ion collisions[1-3], and many astrophysical issues[4-6] as well. In the past four decades, the properties of symmetric matter have been constrained rather satisfactorily, while just in the recent decade, appreciable progress has been achieved on constraining the symmetry energy at saturation and subsaturation densities either through the extraction based on astrophysical observations or in terms of terrestrial data[7-11]. However, the density dependence of the symmetry energy is still poorly known especially at supra-normal densities[3,12-14]. The density dependence of the symmetry energy is rather diverse according to theoretical predictions. It may increase nonlinearly or linearly with the density. Strikingly, some non-relativistic models even predict that the symmetry energy soon goes to negative values at densities several times normal density. This can probably cause severe problems in stabilize the structure of neutron stars. On the other hand, similarly diverse symmetry energy was extracted from analyzing the FOPI/GSI data on the π^-/π^+ ratio in relativistic heavy-ion collisions with various transport models[12-14]. Recently, the required coincidence with data from the ALADIN-2000 collaboration, analyzed by Kumar *et al.*[15], suggested a soft symmetry energy that differs from the super-soft one obtained from the analysis of FOPI/GSI data. More discussions on the status quo of the experimental extraction can be found in a recent work[16]. These extractions really reflect the fact that the density dependence of the symmetry energy is still very illusory, provided the equation of state of symmetric matter used in the transport models is well constrained.

Regardless of the inconsistency in the experimental extractions, the theoretical uncertainty of high-density symmetry energy is regarded to be associated with the tensor force that originates from the exchange terms[17,18]. In the ladder approximation, the exchange terms can be well treated in the Brueckner theory either in the relativistic or non-relativistic frameworks[19,20]. However, the mean-field approximation without exchange terms works more sophisticatedly in high-density matter. It is thus incomprehensible that the tensor force can completely explain the marvellous softening of the high-density symmetry energy. In this work, we decline the strategy using the tensor force to solve the symmetry energy divergence but explore the effect of the non-nucleonic degrees of freedom on the symmetry energy. The results reported here are performed in the relativistic Hartree approximation.

Supported by National Natural Science Foundation of China (NSFC) projects (Nos.10975033 and 11275048).
* Corresponding author. *E-mail address:* wzjiang@seu.edu.cn
Received date: 2013-06-27

2 Modelling

In this work, we consider the non-nucleonic degrees of freedom which include hyperons and quarks. On the hadron level, we make use of the relativistic mean-field (RMF) models. The original Lagrangian of the RMF model was first proposed by Walecka 40 years ago[21]. The Walecka model and its improved versions were characteristic of the cancellation between the big attractive scalar field and the big repulsive vector field. The success of the RMF models is partially attributed to its dynamical description for the spin-orbit interaction. On the quark level, we adopt the MIT bag model[22] to portray the quark phase. The mixed phase is built on the mechanical and chemical equilibriums according to Gibbs conditions.

In the parabolic approximation, the energy per nucleon in isospin asymmetric nuclear matter can be written as

$$\varepsilon / \rho = E / A = e_0(\rho) + E_{\rm sym}(\rho)\delta^2, \qquad (1)$$

where $e_0(\rho)$ is the energy per nucleon in symmetric nuclear matter, $E_{\rm sym}(\rho)$ is the density dependence of symmetry energy, and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry. The symmetry energy in the RMF models reads,

$$E_{\rm sym}(\rho) = \frac{1}{2}C_\rho^2\rho + \frac{k_F^2}{6E_F}, \qquad (2)$$

where C_ρ is the ratio of the ρ coupling constant with the nucleon to the ρ meson effective mass, k_F and E_F are the nucleon Fermi momentum and energy, respectively. In the presence of hyperons, it reads

$$E_{\rm sym}(\rho_B) = \frac{1}{2}C_\rho^2\frac{\rho_N^2}{\rho_B} + \frac{k_F^2}{6E_F}\frac{\rho_N}{\rho_B}, \qquad (3)$$

where ρ_B and ρ_N are the baryon and nucleon density, respectively. As the quarks appear, the system is first in the mixed phase and then in pure quark phase at very high densities. The symmetry energy can be defined according to the similar parabolic approximation of the equation of state,

$$\varepsilon / \rho_B = e_0(\rho_B, Y) + E_{\rm sym}^H(\rho_B, Y)\delta_H^2 + E_{\rm sym}^Q(\rho_B, Y)\delta_Q^2,$$

where H and Q denote hadrons and quarks, respectively, and Y is the quark phase proportion.

3 Results

For simplicity, we just consider the Λ hyperon which usually occupies a majority of hyperons in hyeronized matter. The symmetry energy for various Λ fractions is calculated in symmetric matter at δ=0. The effect of Λ hyperons on the nuclear symmetry energy with the RMF model NL3[23] is illustrated in Fig.1. It is shown in Fig.1 that the symmetry energy is softened clearly with the increase of the Λ fraction. Compared with Eqs.(2) and (3), we see that the softening is dominated by the suppression factor ρ_N / ρ_B. However, even without this suppression factor, the symmetry energy in hyperonized matter is still modified by the isoscalar Λ hyperons provided there exists the isoscalar-isovector coupling Λ_V (for model details, see Ref.[2]). This is clearly seen in the inset of the lower panel of Fig.1 where the potential part of the symmetry energy is displayed. Similarly, if the charged hyperons are included, the potential part of the symmetry energy can be modified even without the isoscalar-isovector coupling. This can be verified

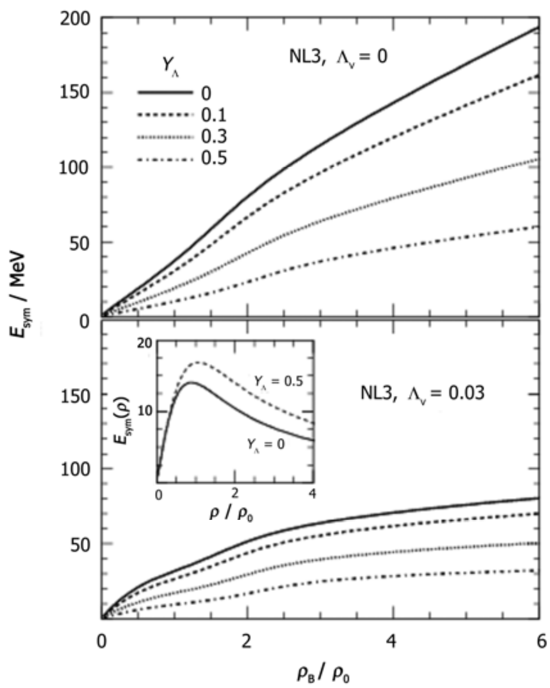

Fig.1 Symmetry energy as a function of density in the presence of the Λ hyperons. The curves depicted are for various hyperon fractions. The upper panel presents the NL3 results without the isoscalar-isovector coupling, while the lower panel include such a coupling that softens the symmetry energy. The potential part of the symmetry energy $E_{\rm sym}^{(p)} = C_\rho^2\rho_B/2$ in the inset of the lower panel is drawn for two cases with and without hyperons.

numerically, while it is beyond the scope of the present work. Nevertheless, we may infer that the symmetry energy may significantly be modified by taking into account the hyperons.

With the increase of density, the hadron-quark phase transition may occur. In this work, quark matter, regarded as the free fermion gas without interactions, is described by the MIT bag model[22]. The mixed phase consists of high-density quark matter and low-density nuclear matter with the quark phase proportion Y being obtained according to Gibbs conditions. The quark phase proportion Y depends on the isospin asymmetry. In this way, the symmetry energy in the mixed phase obtained in symmetric matter cannot simply be used to predict the properties of asymmetric matter because the quark phase proportion changes with the isospin asymmetry in asymmetric matter. Nevertheless, the symmetry energy obtained in symmetric matter is instructive to exhibit its variation tendency in the mixed phase. Shown in Fig.2 is the nuclear symmetry energy as a function of baryon density using the RMF models SLC and SLCd[24-26] combined with the MIT bag model with the bag constant $B=(160\,\mathrm{MeV})^4$ (upper panel) and $B=(180\,\mathrm{MeV})^4$ (lower panel). Apparent decrease of

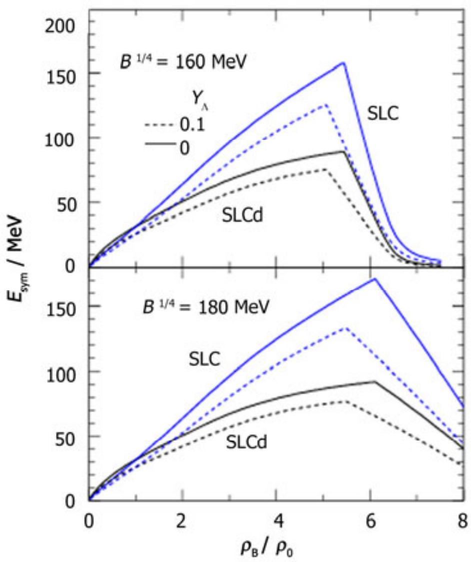

Fig.2 (Color online) Nuclear symmetry energy as a function of density in symmetric matter in the presence of the hadron-quark phase transition. The reflection point from rising to dropping corresponds to the critical density for each model. The two RMF models SLC and SLCd are used. The results in upper and lower panels differ in the value of the bag constant. Above the reflection point, the plotted is the symmetry energy $E^H_{\rm sym}$.

the symmetry energy can be observed after the hadron-quark phase transition occurs. With the increase of density, the nucleon proportion decreases, this causes an apparent reduction of the nuclear symmetry energy. As the nucleon proportion reduces to zero, the nuclear symmetry energy vanishes. Appreciably, it is seen that the change of the symmetry energy is very sensitive to the bag constant. Moreover, in Fig.2 we compare two cases with and without hyperons. It is found that the inclusion of hyperons further softens the symmetry energy as the hadron-quark phase transition occurs.

It is worth noting that the softening of the symmetry energy in the mixed phase is mostly apparent because once the quark phase proportion can be identified at given densities the nuclear symmetry energy would be extracted appropriately by singling out the effect of suppression factor $(1-Y)$. However, the determination of the Y is strongly model-dependent and far from experimental feasibility. Thus, the extraction of the high-density symmetry energy for pure nucleonic matter is not well grounded once the hadron-quark phase transition takes place. Most likely, the high-density symmetry energy extracted from the heavy-ion collisions would be as soft as that presented in this work because of the absence of a reliable discrimination or calibration for dynamically evolutional matter.

4 Conclusion

We have reported the effect of Λ hyperons and quarks on the nuclear symmetry energy at high densities with the RMF models combined with the MIT bag model. The softening of the nuclear symmetry energy is observed in nuclear matter at given Λ fractions. In the presence of the hadron-quark phase transition, the nuclear symmetry energy obtained in the mixed phase reduces quickly with the rise of quark phase proportion. We argue that this softening is apparent but is most likely realistic according to the capacity of the experimental detection.

References

1 Li B A. Phys Rev Lett, 2000, **85:** 4221–4224; ibid. 2002, **88:** 192701.

2 Jiang W Z and Zhao Y L. Phys Lett B, 2005, **617:** 33–39.
3 Li B A, Chen L W, Ko C M. Phys Rep, 2008, **464**: 113–281.
4 Lattimer J M and Prakash M. Phys Rep, 2000, **333:** 121–146; ibid. 2007, **442:** 109–165.
5 Horowitz C J and Piekarewicz J. Phys Rev Lett, 2001, **86:** 5647–5610.
6 Steiner A W, Lattimer J M, Brown E F. Astrophys J, 2010, **722:** 33–54.
7 Chen L W, Ko C M, Li B A, *et al*. Phys Rev C, 2010, **82:** 024321.
8 Newton W, Gearheart M, Li B A. 2011, arXiv:1110.4043.
9 Tsang M B, Stone J R, Camera F, *et al*. Phys Rev C, 2012, **86:** 015803.
10 Wen D H, Newton W G, Li B A. Phys Rev C, 2012, **85:** 025801.
11 Lattimer J M and Lim Y. 2012, ArXiv:1203.4286v1.
12 Xiao Z G, Li B A, Chen L W, *et al*. Phys Rev Lett, 2009, **102:** 062502.
13 Feng Z Q and Jin G M. Phys Lett B, 2010, **683:** 140–144.
14 Russotto P, Trauntmann W, Li Q F, *et al*. Phys Lett B, 2011, **697:** 471–476.
15 Kumar S and Ma Y G. Phys Rev C, 2012, **86:** 051601(R) .
16 Kumar S, Ma Y G, Zhang G Q, *et al*. Phys Rev C, 2012, **85:** 024620.
17 Xu C and Li B A. Phys Rev C, 2010, **81:** 064612.
18 Vidana I, Polls A, Providencia C. Phys Rev C, 2011, **84:** 062801(R).
19 Brockmann R and Machleidt R. Phys Rev C, 2000, **42:** 1965–1980.
20 Song H Q, Baldo M, Giansiracusa G, *et al*. Phys Rev Lett, 1998, **81:** 1584–1587.
21 Walecka J D. Ann Phys (NY), 1974, **83**: 491–501.
22 Chodos A, Jaffe R L, Johnson K, *et al*. Phys Rev D, 1974, **9:** 3471–3495.
23 Lalazissis G A, Konig J, Ring P. Phys Rev C, 1997, **55:** 540–543.
24 Jiang W Z, Li B A, Chen L W. Phys Rev C, 2007, **76:** 054314.
25 Jiang W Z, Li B A, Chen L W. Phys Lett B, 2007, **653:** 184–189.
26 Jiang W Z, Li B A, Chen L W. Astrophys J, 2012, **756:** 56.